FINAL REPORT ON OFFICE OF NAVAL RESEARCH

CONTRACT Nonr-390 (00)

Project NR 046 716

Otto Struve

This project has been in effect between June 14, 1951 and August 14, 1954. ~~It was~~ devoted to the study of a special group of stars designated by the names of two typical representatives of the group, β Canis Majoris and β Cephei.

These stars vary in light, usually with very small amplitudes of the order of a few hundredths of a magnitude; they also vary in color and in radial velocity. About one-half of them show, in addition, variable profiles of the absorption lines. The periods range between 3 1/2 hours and 6 hours.

At the beginning of the project only three or four stars of this type were known. Little was known about their physical characteristics and nothing about the processes that give rise to the observed phenomena.

In the course of our work half a dozen new members of the group have been discovered. We have also carried out detailed studies of ten of them, both photoelectrically and spectrographically.

Our principal results may be summarized as follows:

1) The β Canis Majoris stars are hot gaseous bodies which vibrate in accordance with the law $P\sqrt{\rho}$ = constant. These vibrations (or pulsations) are probably not strictly radial, though the radial components may predominate.

2) There are often two separate vibrations with closely similar periods (for example, 6^h0^m and 6^h3^m as in β Canis Majoris). These vibrations interfere and produce beat periods which range between 7 days and 49 days.

3) The members of the group form a narrow, short sequence in the H-R diagram which is steeper than the main sequence, between spectral types B1 and B3. At B1 the β Canis Majoris stars are about one mag. more luminous than the B1 stars of the main sequence, and their periods are 6 hours. At B3

they merge with the main sequence, their periods then being 3 1/2 hours. At this point their amplitudes, both in light and in radial velocity, are very small. Stars on the main sequence are not known to vibrate. Special conditions (slightly larger luminosity, and therefore smaller density) are required to permit them to oscillate.

4) It is probable that the orientations of the rotational axes of these stars, with respect to the line of sight, explains the variety of combinations of periods, amplitudes, and line-profile variations. This suggests that the vibrations are not strictly spherically symmetrical.

5) In one star we found that the velocity curve is discontinuous on the descending branch of this curve; the spectral lines show three separate components. The vibrations of the stars are believed to cause periodic outward puffs of gas, which ultimately fall back into the star. In several other stars similar phenomena are suspected but they have not yet been fully explored. We believe that the discontinuity of the velocity curves (which were first found in RR Lyrae about eight years ago) represents the key to the problem of Cepheid variation.

6) There are indications that the periods of the β Canis Majoris stars tend to increase steadily at an average rate of about one second per century. This would gradually displace each star along the β Canis Majoris sequence in the HR diagram in the direction of increasing luminosity, decreasing density and slightly increasing temperature. It therefore looks as though this sequence represents the evolutionary track of a B-type star. It would take about one-half million years for a star like ν Pegasi to evolve to the present state of β Canis Majoris. This is in line with previously accepted views regarding the ages of these stars.

The purely photoelectric work, for which this project was intended, was devoted primarily to the study of the β Canis Majoris variable stars, with

occasional studies of other stars, generally of small amplitude and short period. The work has been carried out by Merle F. Walker (July, 1951 to October, 1952), Norman E. Hansen (October, 1952 to March, 1953), and A. D. Williams (March, 1953 to date), with the cooperation of other observers, mainly from the Berkeley Astronomical Department. An amplifier was constructed by Mr. Howard Stackpole, following a circuit designed by Dr. G. E. Kron, and has been used in this work since October, 1952.

Fifteen published notes have resulted from this study, and are listed in the bibliography. A table of information concerning the stars which have received individual attention is as follows:

Star	Period	Light Range	Sp.	Remarks
Nu Eridani	$0^d.1735$	$0^m.05 - 0^m.18$	B2 III	βCMa var., Walker, 1951, 1952 d.
16 Lacertae	0.1692	0.02- 0.11	B2 IV	β CMa var., Walker 1952 a, 1952 c, 1954 b.
HD 199908*	0.079	0.04 -0.07	F2 II	δ Sct?, Walker, 1952 b, 1953 a.
δ Ceti*	0.1612	0.025	B2 IV	β CMa var., Walker 1953 b.
HD 217050*	0.8	0.20 - 0.02	B5ne	Shell star, Walker, 1953 c.
BW Vulpeculae	0.2010	0.19 - 0.26	B2 III	β CMa var., Walker, 1954 a.
δ Scuti	0.1938	0.15 - 0.23	F0	δ Sct., Williams, 1953.
γ Pegasi*	0.1517	0.015	B2 IV	β CMa var., Williams, 1954 a.
Xi_1 CMa*	0.2096	0.00 - 0.04	B1 IV	β CMa var., Williams, 1954 c.

* Variability discovered as a result of this program.

Of the nine stars listed in this table, five were discovered to be variable as a result of this program. Of the four remaining, 16 (=EN) Lacertae was discovered to be variable by Walker in 1950, previous to the present

program; the period of nu Eridani was established as $0^d.1735$ by Walker (1951), thus establishing this previously known variable as a member of the β Canis Majoris class. The color variations of the previously known variables BW Vul (=HD 199140) and δ Scuti were investigated (Walker, 1954 a; Williams, 1953) for the purpose of establishing the mechanism for their variation. Similar color studies were made of nu Eridani, 16 Lacertae, HD 199908, and HD 217050.

Aside from individual star investigations, a search was made for other members of the β Canis Majoris class of variable stars. Walker (1952 e) investigated some 55 stars in a systematic search for such variables but his results were rather unsuccessful; only six stars, other than those noted, were variable or possibly variable. The stars requiring further investigation are listed in the following table:

Star	Period	Light Range	Sp.	Remarks
HD 200857	$>1^d$	0.1	B2	Walker, 1952 b, e.
δ Persei	0.2 ?	0.05 ?	B2 k	Walker, 1952 e.
20 Tauri	0.08 ?	0.02 ?	B9 s	Walker, 1952 e.
23 Sextantis	0.16 ?	0.04 ?	B3	Walker, 1952 e.
(1 Vulpeculae		0.03 ?	(B5 n	Observed together, either may
(HD 182255	?		(B5	be var. Walker, 1952 e.
(HD 176818	?	0.02 ?	(B3	Observed together, either may
(HD 176819			(B2	be var. Walker, 1952 e.
53 Piscium	0.0916	0.01	B3	Williams, 1954 b.

There is now in press a paper by McNamara and Williams on three-color photometry of the β Canis Majoris variables. This paper indicates a correlation between intrinsic colors and periods of the nine β Canis Majoris stars, which have periods shorter than 5 hours; in the range of periods from 5 to 6 hours the colors appear to be constant. Thus we may have indicated the early limit of the "β Canis Majoris phenomenon" as well as a correlation of a type well known in other groups of variable stars.

In addition to the foregoing results, approximately a dozen variable stars, or suspected to be variable, have also have been observed. Four known eclipsing stars and two suspected eclipsing stars (TX Leo, β Lyr, λ Tau, R CMa; HD 22/151, 64 Psc) have been observed, partly to make use of nights of too poor a quality for work on the β Canis Majoris stars and partly to provide information on the times of minimum light for the use of spectrographic observers. The number of nights each of these stars has been observed varies from 3 to 7. Several suspected variables of small light amplitude have also been investigated; these are listed in the following table:

Star	No. night runs	Remarks
RW Aql	7	non-variable?
34G Col	1	sus. δ Sct - non var?
γ Boo	3	pec. - var?
λ Crt	1	sus. δ Sct. non var?
ρ Leo	1	B star - rv var?
σ Sco	2	β CMa variable
β Cep	1	β CMa variable

Walker's unpublished observations of β Cephei indicate that there is no simple relationship between the amplitudes of the velocity and light curves. Unpublished observations of sigma Scorpii, by Williams, obtained simultaneously with spectrographic observations at Mount Wilson, indicate that the phase relation between light and velocity is similar to that found for other β Canis Majoris stars and not "out of phase" as reported earlier by Levee (Ap.J., 115, 402, 1952).

The following observations have been obtained: 23 Sex (6 night-runs, plus 3 night runs with IIprl2" spectrograph), and δ Scuti (20 night runs,

plus 2 3-color Lowell runs). These observations may be sufficient for detailed discussions.

A large measure of the success of this program has been due to our ab_lity to combine the results of this program with the results obtained by other workers. In particular, it should be noted that the combination of simultaneous photometric and spectrographic observations is a powerful method of research.

BIBLIOGRAPHY

McNamara, D. H., and Williams, A. D. The Colors of the Beta Canis Majoris Stars. Ap. J. (in press).

Walker, Merle F. Variability of Nu Eridani. Pub. A.S.P., Vol. 63, 176, 1951.

Walker, Merle F. A Photoelectric Study of 16 Lacertae. Ap.J., Vol. 116, 106, 1952 a.

Walker, Merle F. A New Short-Period Variable Star, HD 199908. Pub. A.S.P. Vol. 64, 192, 1952 b.

Walker, Merle F. A note on 16 Lacertae. Pub. A.S.P., Vol. 64, 195, 1952 c.

Walker, Merle F. Photoelectric Observations of Nu Eridani. Ap.J. Vol. 116, 391, 1952 d.

Walker, Merle F. A Search for Stars of the Beta Canis Majoris Type. A.J. Vol. 57, 227, 1952 e.

Walker, Merle F. Photoelectric Observations of HD 199908. Pub. A.S.P., Vol. 65, 39, 1953 a.

Walker, Merle F. The Light Variability of Delta Ceti. Pub. A.S.P., Vol. 65, 49, 1953 b.

Walker, Merle F. The Light-Variations of HD 217050. Ap.J., Vol. 118, 481, 1953 c.

Walker, Merle F. Three-Color Photoelectric Photometry of HD 199140. Ap.J., Vol. 119, 631, 1954 a.

Walker, Merle F. A Second Photoelectric Study of 16 Lacertae. Ap.J., Vol. 120, 58, 1954 b.

Williams, A. D. Color Variability of Delta Scuti. Pub. A.S.P., Vol. 65, 254, 1953.

Williams, A. D. Light Variability of Gamma Pegasi. Pub. A.S.P., Vol. 66, 25, 1954 a.

Williams, A. D. Variability of 53 Piscium. Pub. A.S.P., Vol. 66, 88, 1954 b.

Williams, A. D. Photometric Observations of ξ_1 Canis Majoris. Pub. A.S.P., Vol. 66, 200, 1954 c.